ESTCP
Cost and Performance Report

(WP-0121)

Reduction of Particulate Emissions in Turbine Engines Using the +100 Additive

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ACRONYMS AND ABBREVIATIONS

ACC	Air Combat Command
AETC	Air Education and Training Command
AFB	Air Force Base
AFPET	Air Force Petroleum Office
AFRL	Air Force Research Laboratory
AFRL/PRTG	Fuels Branch, Turbine Engine Division, Propulsion Directorate, AFRL
CNC	condensation nuclei counter
EERF	Engine Environment Research Facility
EGT	Exhaust Gas Temperature
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
$\mu g/m^3$	micrograms per cubic meter
MASS	Mobile Aerosol Sampling System
NAAQS	National Ambient Air Quality Standards
NIST	National Institute of Standards and Technology
OEM	original equipment manufacturer
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
PND	Particle Number Density
PM10	particulate matter 10 microns or less in diameter
PM2.5	particulate matter 2.5 microns or less in diameter
RPM	Revolutions per minute
SPO	System Program Office
TEOM	tapered element oscillating microbalance
THC	total unburned hydrocarbon
UDRI	University of Dayton Research Institute
UHC	unburned hydrocarbons
UMR	University of Missouri-Rolla
UTC	Universal Technology Corporation
UTRC	United Technologies Research Center
VOC	volatile organic compound
WPAFB	Wright-Patterson Air Force Base
WRDC	Wright Research Development Center

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1.0 EXECUTIVE SUMMARY

Background: The U.S. military spends approximately about $3.5 billion (2003 dollars) per year for aviation fuel. This corresponds to 3 to 4 billion gallons per year (~10% of total U.S. aviation fuel use). The fleet average emission index for particulate matter (PM) has been estimated to be approximately 0.04 g/kg of fuel burned. The total amount of particulate emissions for aircraft in the United States is estimated at 3 million kg per year. Although there is some uncertainty in these estimates, they are consistent with the magnitude being used to estimate global emissions from aircraft (Niedzwiecki, 1998). Airborne particles pose both health and environmental risks. The health effects of particulate matter are related to its ability to penetrate the respiratory system. Particulate matter 2.5 microns or less in diameter (PM2.5) can enter the lungs and end up in lung capillaries and air sacs (alveoli), causing a variety of respiratory problems. Particulate emissions contribute to environmental problems such as visibility impairment (haze) and may contribute to increased signature (infrared emissions) from military aircraft, thus increasing aircraft detectability/vulnerability in enemy territory. Gas turbine engines and ground support equipment are major local sources of PM2.5 particles.

The health and environmental concerns from particulate emissions motivated this work to evaluate the use of the "+100" (BetzDearborn SpecAid 8Q462) additive in jet fuel as a means to reduce the particulate emissions from military gas turbine engines. The +100 additive was developed to increase the thermal stability of JP-8 fuel in order to reduce carbon buildup in fuel system components and injection nozzles. Mostly military aircraft (~3,000) are currently using the +100 additive; however, the additive is also suitable for commercial aircraft due to the similarities of JP-8 and Jet A.

Objectives of the Demonstration: The objectives of the demonstration were to evaluate the reduction in particulate and gaseous pollutant emissions from gas turbine engines using the +100 thermal stability additive in JP-8.

Regulatory Drivers: The National Ambient Air Quality Standards (NAAQS) have a health-based regulation for particulate matter 10 microns or less in diameter (PM10). The regulation limits exposure to air with PM10 concentrations greater than 150 micrograms per cubic meter (µg/m3) in a 24-hour time period and an annual 24-hour exposure of no greater than 50 µg/m3 (EPA Fact Sheet dated November 29, 1996). There is growing evidence that this regulation is insufficient to eliminate serious health and environmental problems for particulate matter with diameters smaller than 2.5 microns (PM2.5). Indeed, the EPA has adopted a revision of the regulation for PM2.5 particles (EPA Fact Sheet dated July 17, 1997). The U.S. Supreme Court recently upheld the constitutionality of the Clean Air Act as interpreted by the Environmental Protection Agency (EPA) in setting the new PM2.5 particulates standard (EPA Fact Sheet dated February 27, 2001). The EPA is currently issuing the final rules establishing the new NAAQS for PM2.5. An extensive air quality monitoring network for PM2.5 is underway to establish which areas meet or do not meet the revised PM2.5 standards. After establishing PM2.5 attainment and nonattainment areas, the PM2.5 regulation is expected to take effect.

Demonstration Results: A very extensive test program to evaluate the +100 additive was completed. Test results showed that the effects of the additive on emissions were dependent on

the engine and power setting. For instance, measurable reductions (~20-25%) (5.5-7.5 million particles per cubic centimeter) in particle number density (PND) were observed with the additive for the TF33 engine at a near cruise condition; however, negligible effects were observed for all other conditions. For gaseous emissions, reductions up to 20% in total unburned hydrocarbon (THC) were observed for all conditions for the second TF33 engine tests; similar results were observed in the T63 tests. However, no evidence of improved particulate or gaseous emissions as a function of operation time with the additive was observed in the T63 long duration tests. For the TF33 tests, chemical characterization of the particles showed increased concentration of polycyclic aromatic hydrocarbons (PAH) as a function of engine power with no significant impacts with the +100 additive. Reductions of up to 40% in PND with the additive were observed for one of the JT8D-9A (T-43 aircraft) engines; however, mixed results were observed for the other three engines.

In summary, for most test cases considered the +100 had negligible effects on emissions. However, despite the inconsistent effects of the additive on emissions, the demonstrated ability of the +100 additive to maintain engine parts clean (Universal Technology Corporation [UTC] & C4e, 2000) merit consideration to implement in these platforms. Implementation costs, compatibility (for B-52) and logistic considerations should be assessed before the additive is implemented in these or other aircraft.

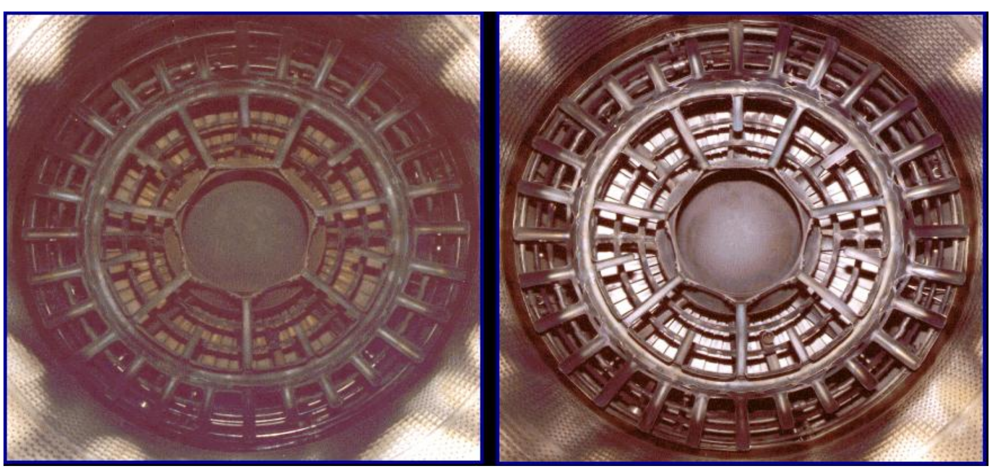
Stakeholder/End-User Issues: Successful demonstration of the benefits of the +100 additive on emissions from large transport aircraft will drive depot managers and stakeholders to implement the technology at their bases to improve quality of life for service members and surrounding communities and to comply with NAAQS regulations. In addition to the environmental benefits, the additive may also reduce maintenance in aircraft engines as has been observed in fighter and C-130 cargo aircraft using JP-8+100. Additive approval from aircraft builders and depot managers (logistics and maintenance organizations) of large cargo aircraft will be critical to the successful transfer of this technology.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The +100 additive (BetzDearborn SpecAid 8Q462) is a fuel additive developed for use with JP-8 military fuel to improve its thermal stability by 100°F. Thermal stability is the ability of the fuel to resist carbon deposits in fuel systems upon heating. The +100 additive package consists of a detergent/dispersant, a metal deactivator, an antioxidant, and a solvent (carrier). The additive package is added to JP-8 at a concentration of 256 mg/l, resulting in JP-8+100. The improvement in thermal stability was necessary because modern aircraft use the fuel to cool a variety of aircraft subsystems. The cooling load applied to the fuel in many aircraft exceeded the thermal stability of the fuel causing carbon deposit formation in fuel lines and nozzles. These deposits increase the maintenance requirements and engine operation anomalies. The deposits also degrade engine performance and increase pollutant emissions.

After initial field testing of the +100 additive, several benefits were experienced. Analyses of field data indicated significant reductions in fuel-related maintenance costs and substantial increases in mean time between fuel-related failures. In addition, the engine components appeared cleaner, with drastically reduced soot buildup (Figure 1). The increase in thermal stability with the +100 additive is mainly attributed to the detergent dispersant. The dispersant is believed to prevent the agglomeration of carbon deposits or precursors formed during the heating of the fuel. This avoids the formation of large particles to help keep the oxidation products soluble in the fuel and off fuel system component surfaces. Although fuel oxidation in a fuel system and during combustion are entirely different processes, this same mechanism may help reduce the amount of particulate emissions in aircraft engine exhaust by reducing coagulation of fine soot particles or oxidized products formed during combustion. Furthermore, the +100 additive will help keep engine components clean, particularly the fuel nozzles, likely improving emissions since the engine operates as designed. Keeping the fuel nozzles clear of carbon deposits helps ensure uniform fuel spray distribution for optimum engine performance.



(a) **(b)**

Figure 2.1. F100 Engine (a) 200 Hrs on JP-8; (b) 200 Hrs on JP-8, Then 56 Hrs on JP-8+100.

The JP-8+100 development started in 1990 with investigations into the cooling requirements for current, next generation, and future aircraft. Studies showed that a threefold increase in the heat-loads for future aircraft and aircraft subsystems compared to the F4 was expected (Harrison, 1990). Since the fuel is the primary heat sink of an advanced aircraft, a fuel that can operate at higher temperatures was needed in order to provide adequate heat sink and enable advanced aircraft technology development. To address this problem, a working group at the Wright Research Development Center (WRDC) (now the Air Force Research Laboratory [AFRL]) recommended the development of a high thermal stability fuel. The additive approach was selected since it is cost-effective and less logistically burdening than developing and fielding a new fuel. Hundreds of additives were tested for effectiveness using a variety of fuel test rigs (Heneghan et al, 1996). In this manner, a novel high-thermal stability jet fuel was successfully developed. JP-8+100 is being used in over 3,000 military aircraft in over 70 locations around the world. It is also being evaluated for use in commercial KLM 747 airplanes.

2.2 PROCESS DESCRIPTION

The +100 additive is expected to reduce particulate emissions from turbine engines primarily by maintaining fuel nozzles free of deposits. Regarding JP-8+100 fuel handling, previous studies have shown that the +100 additive does not add any acute toxicological hazards to JP-8 (Kinkead et al, 1996). Since there are no known special safety issues associated with handling JP-8+100, fuel handlers employed the same safety procedures as used for handling conventional JP-8.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

In 1997, Boeing and the University of Missouri-Rolla (UMR) collaborated to study changes in particulate emissions after an engine had been transitioned to the +100 additive. Their study consisted of making particulate measurements on an F100-PW-100 in F 15A aircraft operating with and without the additive. After the aircraft had been running under standard operating conditions with the +100 additive for 97 hrs, measurements of the particulate emissions were taken. Data from the unpublished report are shown in Figures 2.2 and 2.3. A decrease was observed between 20 and 35% in the particle number density (PND) emissions index between the engine operating with JP-8+100 compared to JP-8 baseline (Figure 2.2). The mechanism of this reduction is not fully understood, but we postulate that the reduction is due to maintaining the cleanliness of engine parts, thus improving system operation.

Recently, the United Technologies Research Center (UTRC) under a research program funded by Fuels Branch, Turbine Engine Division, Propulsion Directorate, AFRL (AFRL/PRTG), conducted experiments to assess the effects of JP-8+100 on the production of particulate emissions from an F119 single nozzle combustor (Liscinsky et al, 2001). The combustor was operated at an air inlet temperature of 500°F and pressures to 200 psi and at several fuel-to-air ratios. As shown in Figure 4, significant reductions in particle size and PND were observed when the combustor was operated with JP-8+100. Reductions of 60-70% in the particulate mass and up to 40% in smoke number were observed. Furthermore, preliminary (unpublished) data from atmospheric combustor tests at AFRL/PRTG also show significant reductions in PND using the +100 additive. These data further support the premise that the +100 additive may reduce particulate emissions from aircraft engines.

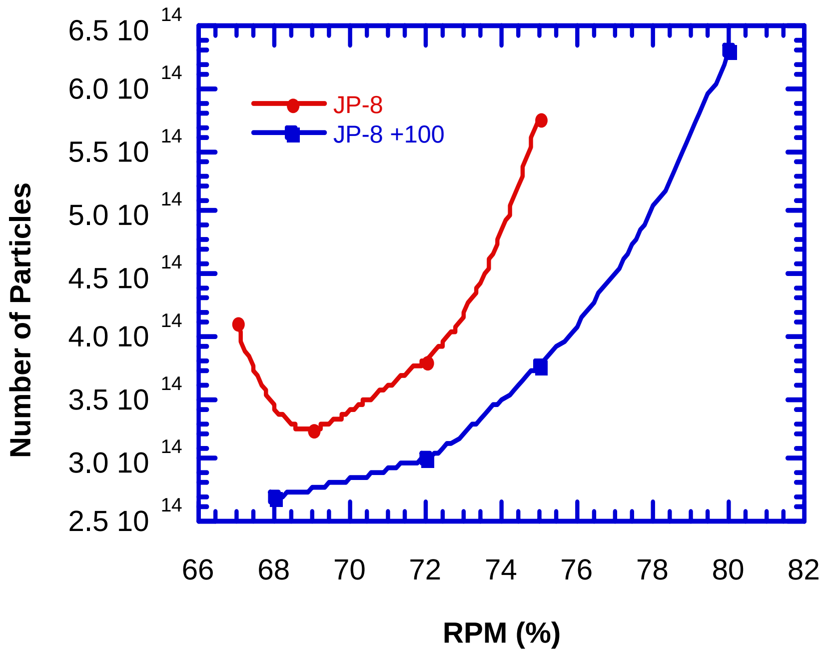


Figure 2.2. Boeing/UMR Particle Number Density for F100 Engine at 68% RPM. (Emissions were taken initially for JP-8 and, after 97 hrs, on JP-8+100.)

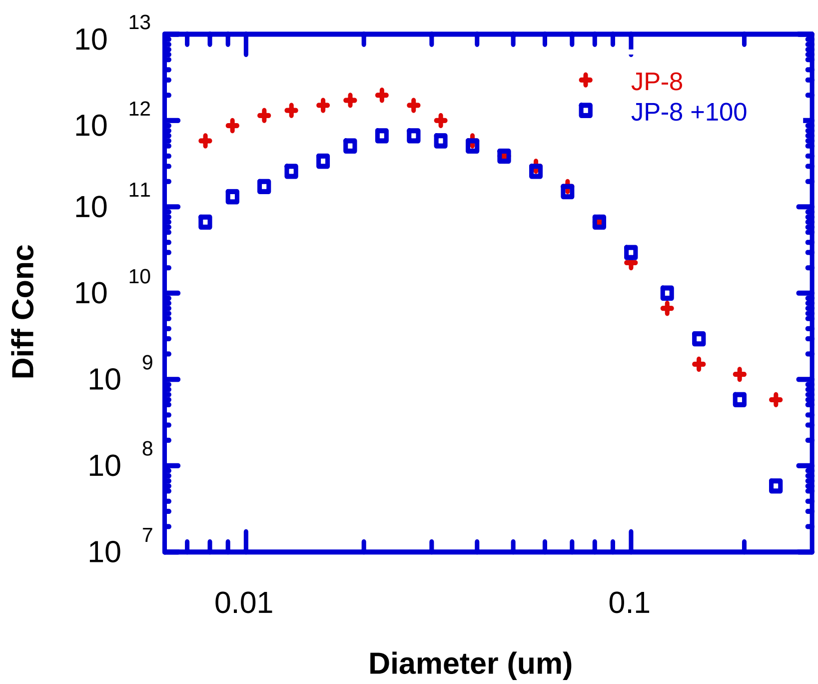


Figure 2.3. Boeing/UMR Particle Size Distribution for F100 Engine at 68% RPM. (Emissions were taken initially for JP-8 and, after 97 hrs, on JP-8+100.)

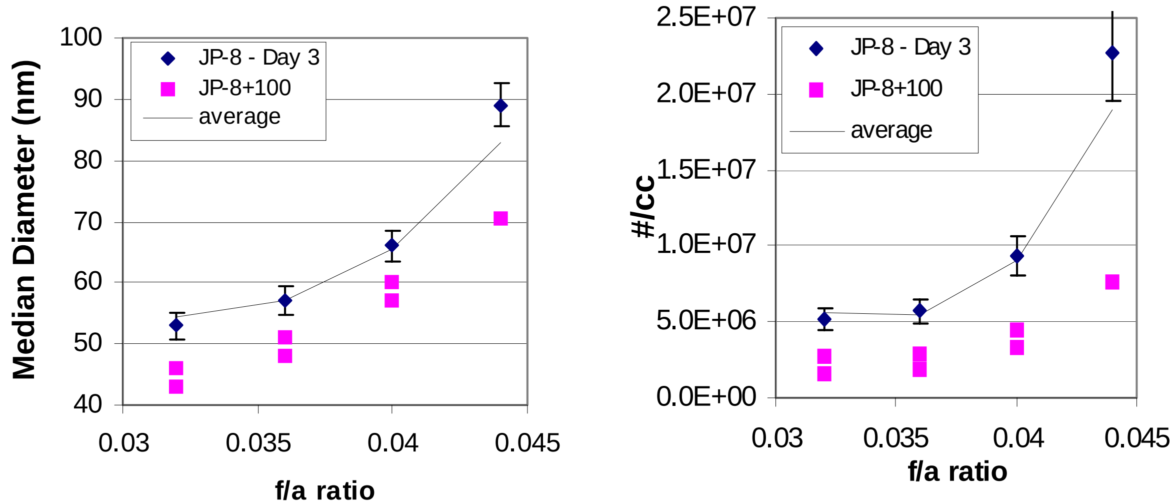


Figure 2.4. Effects of +100 Additive on Particulate Diameter and PND (UTRC studies).

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Fuel additives are the most cost-effective means of improving fuel characteristics and combustion performance in combustion systems. Fuel additive technology has been used for many years in aviation and automotive applications to improve ignition, pollutant emissions, cold flow characteristics, engine performance, fuel lubricity, fuel safety, and fuel efficiency. The +100 additive has been demonstrated to reduce aircraft engine maintenance due to fuel related (coking) problems (Universal Technology Corporation [UTC] & C4e, 2000). Developing additives to treat JP-8 is a more cost-effective, and logistically more favorable technique than reformulating a new fuel. It follows the U.S. military goal of a single fuel for the battlefield. Other ways of improving pollution emissions from combustion systems, i.e., engine redesign and/or retrofit, are cost prohibitive and labor intensive.

Although additive technology is the most cost-effective and a near-term solution to emissions concerns, it does have its limitations. Since the JP-8 specification limits are quite wide, particularly in aromatic and sulfur content, the effectiveness of the +100 additive may not be equal for all JP-8 fuel batches. However, the fuel composition will appear to affect the performance of the additive only if the +100 affects the combustion chemistry. If the +100 benefits are due to cleaning and/or maintaining fuel nozzles free of soot to produce optimum engine operation, then more pronounced effects are expected with the +100 additive for lower quality fuel batches. There are concerns over the use of the +100 additive in large aircraft because of the defueling operations they must undergo in bases that are not equipped to handle the additive. There is evidence that the dispersant in the +100 additive package disarms existing filter coalescers, that is, the coalescers work inefficiently causing poor fuel-water separation. With funding from AFRL/PRTG, improved filter coalescers for use with the +100 additive have been developed. An efficient implementation of these filters has not taken place; however, successful demonstration of the +100 additive to reduce particulate emissions will encourage the implementation of the new filter coalescers and full implementation of the +100 additive at bases with large aircraft.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 3.1 presents the quantitative and qualitative performance objectives of the demonstration, the test metrics and assessment of the actual performance. The magnitude of reduction of 40% or larger was selected to ensure statistical significance based on prior experience.

Table 3.1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (metric)	Actual Performance Objective Met?
Quantitative	1. Reduce particulate matter number density by 40% with JP-8+100 2. Reduce particulate matter mass concentration by 40% when using JP-8+100	1. Reduced particle number density by 30-50% with JP-8+100 2. Reduced particulate matter mass concen-tration by 30-50% or higher when using JP-8+100	1. Mixed results depending on engine and engine condition. In general, performance objectives were not met for PND or mass.
Qualitative	1. Reduce soot buildup in engine compared to operation with JP-8	1. Reduced engine maintenance costs	Not possible to assess due to short duration of additive use. Additive was only used during the evaluation.

3.2 SELECTION OF TEST PLATFORMS/FACILITIES

Demonstrations of the +100 additive technology to reduce particulate emissions were conducted in three test sites. The facilities were: the Air Education and Training Command (AETC) 12th Flying Training Wing at Randolph, Air Force Base (AFB), Texas; the TF33 engine T-9 test facility at Barksdale AFB, Louisiana; and the Environmental Engine Research Facility at Wright-Patterson AFB (WPAFB), Ohio. A summary with the type of engine or aircraft tested is shown in Table 3.2. Description of the work at all locations is discussed in the next section.

Table 3.2. Demonstration Sites.

Engine	Location
TF33	Barksdale AFB, Louisiana
JT8D-9A	Randolph AFB, Texas
T63	Wright-Patterson AFB, Ohio

3.3 TEST FACILITY HISTORY/CHARACTERISTICS

Both the engine-on-wing and static-engine emissions tests consisted of operating the engines at various power settings and taking particulate and gaseous emissions with the engine fueled with and without the +100 additive. A description of the test venues is given below.

Randolph AFB, Texas
Randolph AFB was a convenient location because the base had already been converted to use the +100 additive (used in smaller trainer aircraft). The T-43A was the selected aircraft for the demonstration. The T-43A is the military version of the commercial Boeing 737. It is powered by two Pratt & Whitney JT8D-9A engines and is used for pilot and navigator training. The Air Force has ten T-43As, all of them stationed at Randolph AFB. Representatives from Boeing, the T-43 System Program Office (SPO), and Pratt & Whitney were contacted and informed of the planned demonstration. Boeing, a strong supporter of this program, pursued and received certification of the aircraft for use of JP-8+100. Pratt & Whitney had already certified the JT8D-9A engine for JP-8+100. This demonstration was the only engine-on-wing of this program.

Barksdale AFB, Louisiana
The T-9 test cell at Barksdale AFB is an Air Combat Command (ACC) owned and operated facility used to test the B-52's TF33 engines. It is used mainly to evaluate engine exhaust gas temperature (EGT), vibration, and engine intake characteristics to ensure sound operational capability before installing on the aircraft. In this facility, two TF33 engines, tested 18 months apart, were evaluated to study the efficacy of the additive to reduce emissions at various operating conditions. The engines were operated at five power settings to measure particulate and gaseous emissions throughout the engine's operating regime. Also, for the first tests series the National Institute of Standards and Technology (NIST) chemically characterized the particulate emissions at various engine conditions to assess effects of the additive and power setting on the concentration of carcinogenic polycyclic aromatic hydrocarbons (PAH) in the emitted particles.

T63 Engine Wright-Patterson AFB, Ohio
A T63-A-700 turboshaft engine, employed primarily in helicopter applications, was to evaluate the long-term effects of the additive. The engine is located in the Engine Environment Research Facility (EERF) in the Propulsion Directorate at WPAFB and is used to evaluate turbine engine lubricants, fuels, and sensors in an actual engine environment. These tests were conducted and the data analyzed by WPAFB and University of Dayton Research Institute (UDRI) personnel.

3.4 PHYSICAL SETUP AND OPERATION

Several weeks prior to the demonstration or when necessary, the demonstration team conducted a site visit to the test facility or base to discuss the final test plan and address any special needs or concerns with the tests. Usually 2 days prior to the demonstration, individuals from UMR, Boeing, WPAFB, and in the first Barksdale test, personnel from NIST met at the test location and started the equipment setup. The first day of the demonstration the systems were ready for calibration, background sampling, and system check-up. After ensuring the measuring systems were operating properly, the facility or aircraft operators were contacted to start the tests.

Baseline (JP-8) particulate measurements were taken for engines in test cells and aircraft engines on the runway. The tests consisted of running the engine with JP-8 at a minimum of five operating conditions from idle to higher power. Sufficient particulate and gaseous emissions data were taken at each condition to ensure statistical significance. After completing the sweep of conditions, the engine was brought back to idle and the procedure was repeated. Repeated sweeps or cycles provided independent points at each condition for each fuel to assess uncertainty in the data. After conducting the baseline tests, the engines were fueled with JP-8+100 and the procedure repeated.

The period of performance was between March 2002 and April 2004.

3.5 SAMPLING AND MONITORING PROCEDURES

Various parameters were monitored and analyzed to assess the effectiveness of the additive to reduce pollutant emissions. These included PND, particle size distribution, gaseous emissions, and soot chemical characterization (TF33 Test I). The particulates measurements in the field were performed by UMR using a combination of instrumentation housed in its Mobile Aerosol Sampling System (MASS) trailer. The various instruments and techniques used for these measurements are described in section 3.6.4 of the final report (Corporan, 2005).

3.6 ANALYTICAL PROCEDURES

The analytical procedures used were based on the widely accepted UMR technique (described in Section 3.6.4 of the final report), which measures various physical characteristics of the engine's particulate exhaust. By evaluating the PND, particle size distribution, and particle chemical composition (first TF33 tests), an assessment can be made to determine if the additive is affecting the formation or oxidation of particles, and the concentration of harmful chemicals in the particulate matter.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Four demonstrations were completed under this Environmental Security Technology Certification Program (ESTCP) effort to assess the efficacy of the +100 additive to reduce particulate emissions from turbine engines. The demonstrations were:

1. Four JT8D-9A engines on T-43 aircraft at Randolph AFB
2. TF33 engine at Barksdale AFB
3. Second TF33 engine at Barksdale AFB (TF33 II)
4. T63 engine at Wright-Patterson AFB

All engines under this demonstration program except the T63 were tested at a minimum of five power settings with and without the +100 additive. PND, particle size distribution, and fuel chemical composition were analyzed. Each engine power setting was held 5 to 10 minutes to ensure steady-state operation and gather sufficient data for statistical analysis. Several size distribution measurements were taken at each power setting to assess particle size consistency throughout the test period. Particulate data for the TF33 and T-43 demonstrations are presented in Tables 4.1, 4.2, 4.3, and in Figure 4.1. The PND data trends were fairly consistent as a function of engine power except for the abnormally high PND for the cruise power for engine #608 (Figure 5). The large discrepancy may be due to a dilution air leak or an instrument malfunction.

Table 4.1. Particle Number Density Data for TF33 Test I.

	Engine Power Setting				
	58%	**70%**	**80%**	**90%**	**98%**
Average JP-8 (#/cm^3)	20×10^6	26×10^6	30×10^6	44×10^6	35×10^6
%error JP-8	11%	11%	11%	6%	28%
Average JP-8+100 (#/cm^3)	17×10^6	23×10^6	26×10^6	45×10^6	31×10^6
%error JP-8+100	18%	17%	20%	21%	12%
%change with additive	**-13%**	**-11%**	**-14%**	**2%**	**-12%**

Table 4.2. Particle Mean Diameter for T-43 Aircraft Engines Using JP-8 and JP-8+100.

Engine 613			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	53.3	55.8	4.6%
Approach	68.2	62.3	-8.7%
Cruise	82.0	75.0	-8.5%
Climb	78.0	74.3	-4.8%
Hi-Power	83.0	72.8	-12.3%

Engine 636			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	52.0	52.0	0.0%
Approach	70.0	71.0	1.4%
Cruise	75.0	74.3	-0.9%
Climb	78.0	78.3	0.4%
Hi-Power	83.0	76.7	-7.6%

Engine 608			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	50.0	62.8	25.5%
Approach	71.0	74.7	5.2%
Cruise	74.0	80.3	8.6%
Climb	81.0	80.0	-1.2%
Hi-Power	78.0	80.0	2.6%

Engine 607			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	47.0	58.3	24.1%
Approach	62.0	63.0	1.6%
Cruise	71.0	73.0	2.8%
Climb	73.0	74.7	2.3%
Hi-Power	66.0	78.0	18.2%

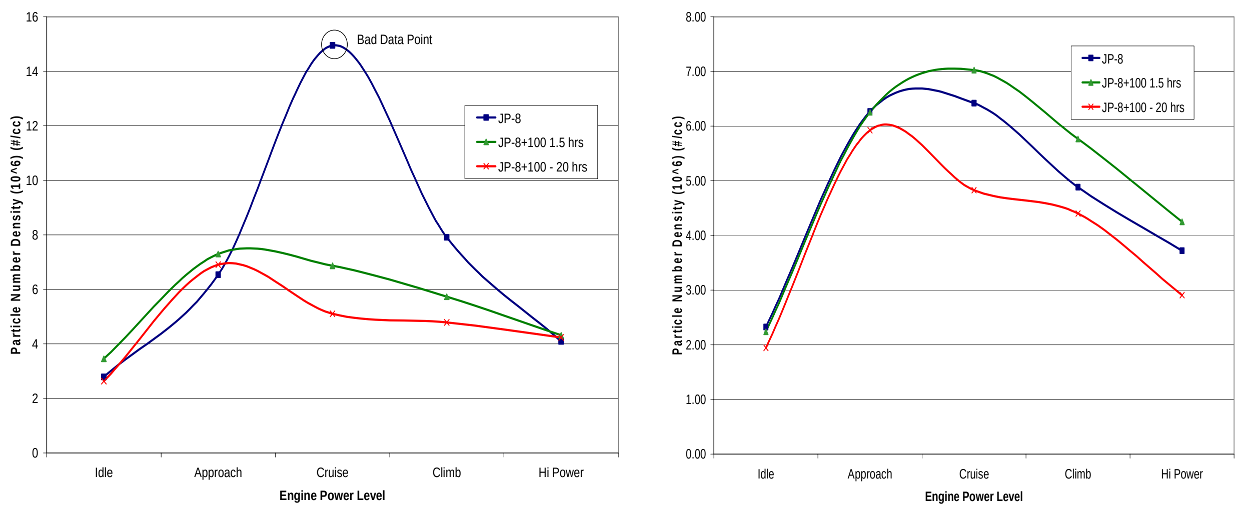

Figure 4.1. PND as a Function of Power Setting for T-43 Engines 608 and 636.

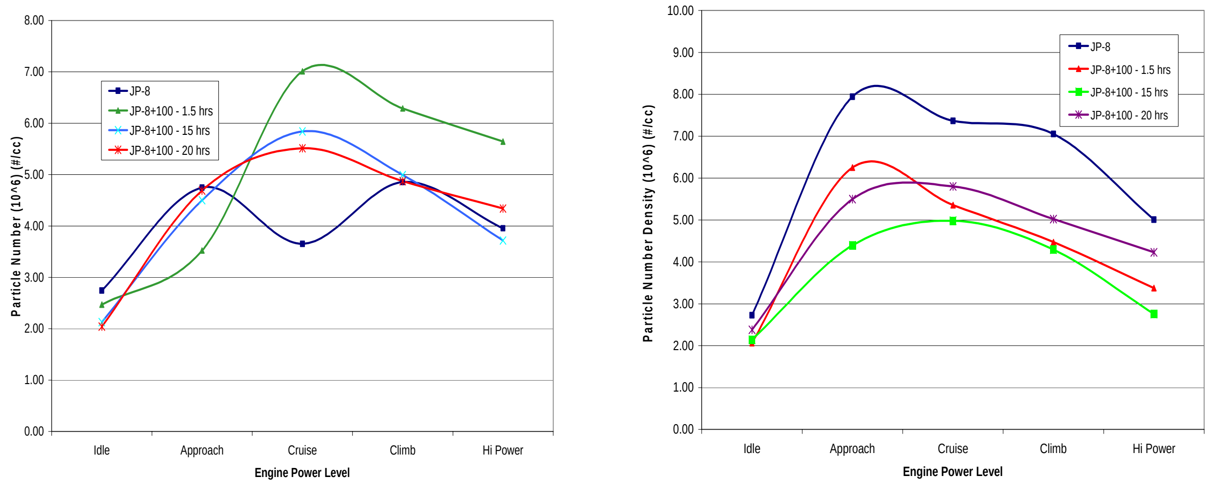

Figure 4.2. PND as a Function of Power Setting for T-43 Engines 607 and 613.

Table 4.3. Particle Number Density (10^6) for Different Power Settings TF33 Tests II.

Test Day and Fuel Used	Average or Error (1-sigma)	58	70	80	90	98
Monday (JP-8 all)	Average	32.9	28.6	30.9	40.2	36.0
Monday (JP-8 all)	Error	38%	59%	64%	49%	66%
Monday (JP-8 first five runs)	Average	27.6	19.6	20.5	29.5	25.2
Monday (JP-8 first five runs)	Error	40%	31%	29%	15%	22%
Tuesday (JP-8 + 100)	Average	23.0	21.7	20.1	25.8	21.2
Tuesday (JP-8 + 100)	Error	15%	16%	25%	17%	15%
Wednesday (JP-8+100)	Average	22.3	19.1	19.1	25.5	20.6
Wednesday (JP-8+100)	Error	7%	7%	7%	5%	10%
Thursday (JP-8+100)	Average	18.6	16.8	16.8	22.2	17.3
Thursday (JP-8+100)	Error	10%	12%	13%	6%	10%

4.2 PERFORMANCE CRITERIA

The performance criteria for the demonstration are shown in Table 4-4. The particle concentration was designated as the only primary criterion because it was considered the most reliable and easier to measure parameter for the demonstration. A 40% or higher reduction was selected to ensure statistical significance based on previous experience. Due to the complexities associated with combustion processes in turbine engines, it was unrealistic to expect a significant reduction in particulate emissions with the additive for all engines and test conditions. Therefore, a 40% or larger reduction in PND for 70% or more of the test conditions was considered reasonable to confirm the reduction in particulate emissions with the additive.

Table 4.4. Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Reduced PM emissions	40% or higher reduction particle number density for 70% for all tests	Primary
Reduced gaseous pollutant emissions	20% reduction in CO, NO_x and unburned hydrocarbons (UHC) emissions for all test conditions	Secondary
Reduce size of PM	30% reduction in mean particle diameter	Secondary
Reduced amount of PAH	50% reduction in PAH concentration on particulate matter	Secondary
Visibly cleaner engine	Cleaner turbine blades and exhaust	Secondary

Table 4.5. Actual versus Expected Performance.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
Reduced PM emissions	Greater than 40% in particle number density for 70% of tests	Average condensation nuclei counter (CNC) measurements and determine uncertainty for each condition	Only one case showed a maximum of 40% reduction in PND.
Reduced gaseous pollutant emissions	20% reduction in CO, NOx, and THC for all test conditions	Average gaseous emissions measurements and determine uncertainty for each condition	Additive reduced THC by 15-22% in TF33 & T63 engines. It had statistically insignificant effects on all other gaseous emissions. No effect JT8D engines.
Reduce size of PM	30% reduction in mean particle diameter	Average particle mean size measurements from DMA and determine uncertainty for each condition	Minor reductions in particle mean diameter.
Reduced amount of PAH	50% reduction in PAH concentration on PM	Average concentration of PAHs in particulates and determine uncertainty for each condition	Additive showed no effect on PAH content of particulates.
Visibly cleaner engine	Cleaner hot section/exhaust	Reduced engine maintenance. Compare images (photos) before and after tests (longer term [tenths of hrs] effect)	Engine maintenance could not be assessed due to short-term use of the additive.

4.3 DATA EVALUATION

4.3.1 TF33 Tests I at Barksdale Air Force Base

4.3.1.1 Particulate Matter Emissions

PND values for the TF33 were generally between 2.0 x 10^7 and 5.0 x 10^7 particles per cm^3 with and without the additive. As expected, lower PND values were obtained at the lower power setting, which increased as the engine power was increased until the engine setting of 90%. At

maximum power (98%), the particulate level decreased to the values of the 80% power, probably due to higher efficiency (improved soot and volatile particle combustion) at the higher power level. The first 40 tests were conducted with JP-8 and showed very good reproducibility (within 15%) at most power settings. Larger errors were observed at high power and when the engine operated on JP-8+100. Engine operation with the additive initially did not appear to impact the particulate emissions. After run number 70 (5 hrs of use of +100), there appeared to be reductions in PND at the 58, 70, and 80% power test conditions; however, a trend of increases in PND at the 90 and 98% conditions were also observed. It is difficult to assess if there was a time dependent effect with the additive (improved emissions as additive was used) since the reduction was observed only during the last three or four run conditions. The PND data, listed in Table 4.4, show that there was a reduction in PND for four of the five conditions; however, the calculated error (1-sigma) was higher than the observed reduction, rendering the reductions statistically insignificant. Although at the end of the test program the trends showed reductions in PND for the lower power conditions, the lack of sufficient test runs precluded an acceptable statistical analysis with those data. Longer test times were needed to investigate the long-term effects of the additive on particulate emissions. However, these are usually not practical and introduce uncontrollable factors such as different fuels, atmospheric conditions, and even engine wear and tear that can potentially impact emissions and cloud the real effects of the additive.

Particle diameters were in the 60-115 nm range, thus, significantly smaller than 2.5 µm (particulate matter 2.5 microns or less in diameter [PM2.5].) As expected, the particle mean size increased as a function of power setting. Slight reductions in particle diameter with the additive were observed for all conditions tested. The largest reduction at 9% in diameter was observed for the idle condition (58%); however, considering the calculated error for each data set, the differences in particle mean diameter between the fuels are considered statistically insignificant.

4.3.2 T-43 Tests at Randolph Air Force Base

4.3.2.1 <u>Particulate Emissions</u>

Average values for the PND data for all four engines as a function of power setting and run time are shown in Figures 5 and 6 above. Precision (repeatability) errors for the PND measurements for most tests were 10-20%. All four engines produced similar PND values and trends as a function of power setting. Values of 2.0-3.0 x 10^6 particles per cm^3 were observed for the idle condition, while 4.0-8.0 x 10^6 particles per cm^3 were common for the mid-power levels. At the higher power setting, the values decreased to 3.0-5.0 x 10^6 particles per cm^3 for most conditions. Comparison of particulate emissions between the engines operating with JP-8+100 and the baseline fuel showed no consistent trend. For engine 613, an average reduction of approximately 40% in PND with the +100 additive was observed for all power conditions. Also, significant variation in the PND was observed as a function of time but with no clear trend. For engines 608 and 636, there also appears to be a slight reduction in PND for the engines operating for 20 hrs with the additive; however, there was also an increase in PND for engines 607 and 636 after a 1.5 hour JP-8+100 use. The latter could be the result of increased particulate emissions as the engine was cleaned with the additive; however, these results were inconsistent with all engines and power settings. Longer test times with the +100 additive could have shed light into the additive's long-term effects on emissions.

Listed in Table 4.2 are the average mean particle diameters for the engines, fuels, and conditions tested. The particle diameter is an important parameter since its relation to mass is to the third power. Mean particle diameters for the four JT8D-9 engines varied from 50 to 83 nm, with the smallest particles at the idle condition and the largest at one of the three highest power settings. The small mean particle diameter at idle may be partly the result of large concentrations of volatile particles resulting from uncombusted or partially combusted jet fuel. Separation of volatile and nonvolatile particles was not performed in this study. For engine 613, reductions in the particle size were observed with the additive for all conditions except idle. For two of the four engines (607 and 608), there were increases in particle size with the additive ranging from 1.6 to 25%, with the largest increases occurring at the low power setting (idle). Negligible changes in particle size were observed for engine 636. From these results, it is clear that the impacts of the +100 additive on engine particulate emissions cannot be generalized since they differ significantly depending on engine and test conditions.

4.3.3 TF33 Tests II at Barksdale Air Force Base

4.3.3.1 <u>Particle Emissions</u>

Average particle concentration values for each test condition per day with their respective one standard deviation errors are shown in Table 4.3. The engine was operated with JP-8 for the first 40 test runs and subsequent tests with JP-8+100. A significant increase in PND with the continuous use of JP-8 was observed. This sharp increase in particle loading with JP-8 is not well understood, and it could be due to several factors, including progressive fouling of fuel nozzles, slight differences in engine operating conditions, changes or uncertainties in dilution flows, unknown instrumentation artifacts, or a combination of these. Addition of the +100 additive appeared to have reduced the PND to their original levels with JP-8. Subsequent use of JP-8+100 increased particulate emissions which then stabilized to values between 15.0×10^6 to 25.0×10^6 for all the conditions tested.

The effects of the additive on particulate mass were insignificant at the lowest three power settings. At full power, there appeared to be an increase in particulate mass with the additive; however, a T-test analysis revealed that it was statistically insignificant. The only power setting that showed statistically significant reductions in particle mass sample averages was at the 90% setting. Approximately 30% reduction in particulate mass emissions was observed at the 90% condition.

4.3.4 T63 Tests at Wright-Patterson Air Force Base

4.3.4.1 <u>Particle Emissions</u>

PND data as a function of test time for the cruise condition during the long-duration T63 tests show that the PND increased by nearly 50% from 13 to 48 hrs of operation with JP-8. This is believed to be the result of fuel nozzle fouling, which potentially caused non-uniform fuel spray and eventual degradation of the combustion performance. Continuous use of the baseline fuel did not further degrade/increase engine particulate emissions. After 87.5 hrs of test time, JP-8+100 was used. The +100 additive did not effect a change in PND until after 40 hrs of use in

which a marginal reduction of 15% was observed. Further use of the additive had negligible effect on the PND.

The particle size distributions show that the mean particle diameters for the baseline and +100 fuels were very similar for all test runs. The concentration of particles peaked at the 88 hr mark and decreased slowly with use of the additive. Consistent with the PND data, negligible differences were observed between the 129- and 175-hr size distribution and trends, thus no changes in mass occurred during this time period.

4.4 TECHNOLOGY COMPARISON

As discussed in Section 4.1, Performance Data, the impact of the +100 additive on engine emissions is highly dependent on engine condition and technology. However, for most test cases evaluated, the +100 additive was ineffective in reducing particulate matter emissions relative to JP-8. Long-term evaluations of the additive are recommended to assess its ability to keep fuel nozzles and other engine components clean, in order to quantify the effects of a potentially cleaner engine on emissions.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The operational costs for the +100 additive conversion of the T-43 and B-52 aircraft at Randolph AFB and Barksdale AFB, respectively, are mostly due to the cost of the additive. All other potential costs are considered relatively low. A summary of these operational and the implementation costs is presented in Table 5-1.

Table 5.1. +100 Additive Operational and Implementation Costs for T-43 and B-52 Aircraft.

	Direct Costs			
	Start-Up		Operation and Maintenance	
Aircraft/Air Force Base	**Activity**	**$ Dollars**	**Activity**	**$ Dollars**
T-43/Randolph AFB	Additive Injection System	$ -	*Additive per yr (Based on 3.6 million gallons JP-8)	$18,200
	Defuel Trucks			
	Additive Storage Tanks	$15,000		
	Installation	$ -		
	Total	**$15,000**		**$18,200**
B-52/Barksdale AFB	Training Operators	$6,000	*Additive per yr (Based on 41.6 million gallons JP-8)	$208,000
	Additive Injection System	$52,500		
	Defuel Trucks	$145,000		
	Storage Tanks & Misc	$15,000		
	Site Verification	$11,250		
	Installation	$21,000		
	Travel & Mobilization	$13,000		
	Total	**$263,750**		**$208,000**

*****Additive cost based on average annual fuel consumption multiplied by $0.005 per gallon JP-8 fuel.

5.2 COST ANALYSIS

Based on experience with fighter and cargo aircraft presently using the +100 additive, reduced coking of fuel nozzles and therefore reduced engine maintenance due to fuel nozzle and combustor anomalies are expected with the use of the additive. However, for this demonstration the aircraft or engines were operated with the additive for only 1 week, which did not allow a long-term (several years) assessment on the maintenance benefits of the additive. Since these benefits are highly dependent on engine type and operation, it is impossible to properly estimate potential cost savings in maintenance (e.g., time between engine overhauls) and increased engine life caused by the additive without a long-term study. Since consistent benefits in emissions were not observed in this program, the additive appears to offer no cost benefits in these platforms.

5.2.1 Implementation Costs for B-52 Aircraft at Barksdale AFB

A study conducted by Mr. Ozzie Pinkham of C4e Inc. (on contract with AFRL/PRTG) identified four options for the implementation of the +100 additive at Barksdale AFB for use in the B-52 aircraft. Options and associated costs are described in Appendix A of the final report.

5.2.2 Implementation Costs for T-43 Aircraft at Randolph AFB

Based on discussions with base officials, there is no cost for implementation of the +100 additive on the T-43A trainer aircraft at Randolph AFB. Since the base already operates smaller trainers (e.g., T-37s and T-38s) with JP-8+100, the infrastructure required to support the additive use in the T-43 aircraft (additive injection carts, refueler trucks, etc.) is already in place. Costs associated with the increased workload as the result of additive injection are expected to be minimal. An additional defueling truck might be required to facilitate the aircraft defuels. The use of the additive may actually simplify on-base defueling operations since there will no longer be a need to have separate defueling tanks for JP-8 and JP-8+100. Details on the implementation of the additive for T-43 planes at Randolph AFB are discussed in Appendix B of the final report.

5.3 COST COMPARISON

As previously mentioned, use of the +100 additive on these platforms is expected to provide benefits on reduced engine maintenance due to cleaner fuel nozzles and hot section parts. These benefits, however, could not be demonstrated in this program due to the short duration of the demonstration. Benefits in emissions were inconsistent and highly dependent on engine and engine condition. Since benefits were not observed in this study, a cost comparison of the +100 additive with conventional technologies (e.g., engine retrofits) is not warranted.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The relatively low cost of the additive at $0.005 per gallon of fuel is expected to decrease due to increased additive production if used in these and other cargo or bomber aircraft.

6.2 PERFORMANCE OBSERVATIONS

Detailed performance observations are discussed in Section 4.

6.3 SCALE-UP

Full-scale implementation of the +100 additive on the T-43 or B-52 aircraft will require approval from the aircraft manufacturer, SPO, and base and/or unit commander. The implementation costs listed in Table 5.1 are estimates based on previous experience on implementing the additive at other bases.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Technical challenges, mostly associated with the additive disarming of filter coalescers, will adversely affect the implementation of this additive on any large aircraft. More details are provided in Section 2.4. Implementation of newly developed filter coalescers should alleviate most of these concerns.

6.5 LESSONS LEARNED

Although the effects of the +100 additive on engine particulate emissions were inconsistent, the additive was observed to have no detrimental effect on the emissions or performance of the engines tested. Longer duration tests are required to determine the potential of the additive to reduce engine maintenance and prevent degradation of engine emissions.

6.6 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES

A study conducted by C4e Inc. to investigate the feasibility of converting the existing fleet of T-43A aircraft at Randolph AFB to JP-8+100 was completed. The study showed that defueling operations with this aircraft were not a major issue since defuels were minimum and usually occurred on station. Therefore, there appear to be no major issues to the implementation of the additive in the T-43. However, further coordination and acceptance from the aircraft SPO and Boeing will be required before the AETC grants the approval to convert the T-43 fleet to use the +100 additive.

Implementation of the +100 additive on the B-52 is more challenging since the aircraft lands in bases not equipped to handle the additive. High blend back ratios (currently set at 100 gallons JP-8 per gallon of JP-8+100) have been established to prevent the filter problems. This complicates the implementation of the additive in locations not equipped (e.g., defuel tanks and refueling trucks) to handle these highly demanding defueling and blending operations. Additive

implementation on the B-52 will need to be approved by the airframer (Boeing), the Air Force Petroleum Office (AFPET), the B-52 SPO, and base officials.

Based on this demonstration, the increased cost and logistics burden associated with using the +100 additive in these platforms cannot be justified since no clear (or sufficient) benefits in emissions were observed. However, a more extensive program should be established on these aircraft to study the potential benefits of the additive on reduced engine maintenance, as has been observed in other platforms.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Based on the results from this demonstration, the +100 additive will not greatly influence the PM emissions from turbine engines and therefore will not help meet regulatory requirements for particulate matter. Additional research is recommended for the assessment of the additive on unburned hydrocarbons since reductions in these volatile organic compounds (VOC) were observed in two types of engines.

7.0 REFERENCES

1. Corporan, E., and O. Monroig. "Reduction of Particulate Emissions in Turbine Engines Using the +100 Additive," Final Report - ESTCP Project No. PP-200121, June 2005.

2. Corporan, E., M.J. DeWitt, O. Monroig and M. Wagner. "Influence of Fuel Chemical Composition on Particulate Matter Emissions of a Turbine Engine," GT2004-54335, Proceedings of ASME Turbo Expo 2004, Vienna, Austria, 2004.

3. Dockery, D. W., J. H. Ware, B. G. Ferris, Jr., F. E. Speizer, N. R. Cook, and S. M. Herman. "Change in Pulmonary Function in Children Associated with Air Pollution Episodes," J. Air Poll. Control Assoc. 32:937-942, 1982.

4. Environmental Protection Agency. EPA's Revised Particulate Matter Standards. http://www.epa.gov/ttn/oarpg/naaqsfin/pmfact.html, July 17, 1997.

5. Harrison III, W.E., "Aircraft Thermal Management: Report of the Joint WRDC/ASD Aircraft Thermal Management Working Group," WRDC-TR-90-2021, February 1990

6. Heneghan, S.P., S. Zabarnick, D.R. Ballal, and W.E. Harrison III. "JP-8+100: The Development of High-Thermal-Stability Jet Fuel," Journal of Energy Resources Technology, Vol. 118, pages 170-179, September 1996.

7. Howard, R. P. et al. "Experimental Characterization of Gas Turbine Emissions at Simulated Flight Altitude Conditions," AEDC-TR-96-3, September 1996.

8. Kalt, D.H., S. Zabarnick, S.D. Anderson, and P.D. Liberio. "Fuel and Fuel System Materials Compatibility Test Program for a JP-8+100 Fuel Additive Package," AFRL Tech Report No. AFRL-PR-WP-TR-2000-2021, March 1999.

9. Kinkead, E.R., R.E. Wolfe, M.L. Feldmann, H.F. Leahy, and W.W. Jederburg. "Acute Toxiticy Evaluation of JP-8 Jet Fuel and JP-8 Jet Fuel Containing Additives," AFMC Tech Report No. AL/OE-TR-1996-0136, February 1996.

10. Landau, M., et al. "Jet Aircraft Engine Exhaust Emissions Database Development—Year 1990 and 2015 Scenarios," NASA Contractor Report 4613, July 1994.

11. Lippmann, M., and P. J. Lioy. "Critical Issues in Air Pollution Epidemiology," Envir. Health Perspec. 62:243-258, 1985.

12. Liscinsky, D.S., M.B. Colkett, D.J. Hautman, and B. True. "Effect of Fuel Additives on Particle Formation in Gas Turbine Combustors," AIAA 2001-3745, AIAA Joint Propulsion Conference 2001.

13. Niedzwiecki, R. "Aircraft Technology and its Relation to Emissions," Chapter 7 of Report of The Intergovernmental Panel on Climate Change, IPCC, 1998.

14. SAE AIR 5892 “Nonvolatile Exhaust Particle Measurement Techniques,” SAE Publications, Society of Automotive Engineers, 2004.

15. Schwartz, J., “Particulate Air Pollution and Chronic Respiratory Disease,” Environ. Research 62:7, 1993.

16. Thompson, A. M., “Atmospheric Effects of Aviation: First Report on the Subsonic,” NASA Reference Publication 1385, 1996.

17. Universal Technology Corporation (UTC) and C4e, Inc., “Study of JP-8+100 Impact on C-130 Aircraft at 123 AW, KY ANG,” September 2000.

18. Wilson R., and J. Spengler. “Particles in Our Air Concentrations and Health Effects,” Harvard University Press, 1996.

APPENDIX A

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